Astronomy Reports, 2013, Vol. 57, No. 2, pp. 128–133. DOI: 10.1134/S1063772913020078

arXiv:1301.7011v1 [astro-ph.GA] 29 Jan 2013

Analysis of Determinations of the Distance between the Sun and the Galactic Center

Z. M. Malkin

Pulkovo Observatory, St. Petersburg, Russia
St. Petersburg State University, St. Petersburg, Russia
e-mail: malkin@gao.spb.ru

Abstract

The paper investigates the question of whether or not determinations of the distance between the Sun and the Galactic center R_0 are affected by the so-called "bandwagon effect", leading to selection effects in published data that tend to be close to expected values, as was suggested by some authors. It is difficult to estimate numerically a systematic uncertainty in R_0 due to the bandwagon effect; however, it is highly probable that, even if widely accepted values differ appreciably from the true value, the published results should eventually approach the true value despite the bandwagon effect. This should be manifest as a trend in the published R_0 data: if this trend is statistically significant, the presence of the bandwagon effect can be suspected in the data. Fifty two determinations of R_0 published over the last 20 years were analyzed. These data reveal no statistically significant trend, suggesting they are unlikely to involve any systematic uncertainty due to the bandwagon effect. At the same time, the published data show a gradual and statistically significant decrease in the uncertainties in the R_0 determinations with time.

1 Introduction

Accurate knowledge of the distance between the Sun and the Galactic center R_0 is very important for many problems associated with the structure and evolution of the Universe, as well as for astrometric applications. For example, the need to determine the effect of Galactic aberration on the proper motions of radio sources more precisely motivated our study of the accuracy of R_0 determinations [1].

Like any quantity derived from observations, determinations of R_0 have both random and systematic uncertainties. The systematic uncertainties are most dangerous in terms of using the corresponding results in various applications. Such systematic uncertainties could be due to instrumental and methodical uncertainties, or uncertainties in a theory used to interpret the measured values. Alongside these, subjective uncertainties that are not associated with the accuracy of the observations or data processing can arise. One example is the "bandwagon effect". This refers to the possibility that only measured results corresponding fairly well to the expected values are published; i.e., these are results that differ from commonly accepted expectations (or values published earlier) by a “reasonable” (usually small) amount. However, the fact that the overwhelming majority of published data were honestly derived from observations suggests that, even if they are filtered by publication selection, published values should gradually approach the true value. Therefore, the presence of a trend in the published determinations of some quantity may indicate a role played by the bandwagon effect (naturally, taking into account possible real variations of this quantity with time).

In our case, a role of the bandwagon effect has been suspected in a number of reviews devoted to R_0 determinations (e.g., [2-4]), which can be significantly subject to this systematic uncertainty. These suspicions were based on claims of systematic variation of the published R_0 values with time. However, the trends obtained in [2-4] do not agree with each other (this is discussed in Section 3 in more detail). Moreover, many results refer to out-of-date publications that are almost irrelevant now. The current study is aimed at elucidating whether or not published values of R_0 obtained over the past 20 years display appreciable time-dependent variations.

2 Determinations of R_0 used in the analysis

We used R_0 determinations published between 1992 and 2011. Those interested in earlier data can refer to the reviews [2,3,5,6]. We used all published data except those refined later. Thus, we did not use the result of [7], revised in [8], the result of [9], revised in [10], and the result of [11], revised in [12] and later in [13].

In cases when the estimates of both random (ε_{stat}) and systematic (ε_{syst}) uncertainties are available, we calculated the total uncertainty as the square root of the sum of their squares, $\varepsilon = \sqrt{\varepsilon_{stat}^2 + \varepsilon_{syst}^2}$. The corresponding data are presented in Table 1.

Table 1: Values of R_0 for which random and systematic uncertainties are available

Reference	R_0, kpc
[14]	$R_0 = 7.52 \pm 0.10 \,|_{stat} \pm 0.35 \,|_{syst}$
[15]	$R_0 = 7.94 \pm 0.37 \,|_{stat} \pm 0.26 \,|_{syst}$
[16]	$R_0 = 8.07 \pm 0.32 \,|_{stat} \pm 0.13 \,|_{syst}$
[13]	$R_0 = 8.33 \pm 0.17 \,|_{stat} \pm 0.31 \,|_{syst}$
[17]	$R_0 = 8.28 \pm 0.15 \,|_{stat} \pm 0.29 \,|_{syst}$
[18]	$R_0 = 8.24 \pm 0.08 \,|_{stat} \pm 0.42 \,|_{syst}$
[19]	$R_0 = 8.3 \pm 0.46 \,|_{stat} \pm 1.0 \,|_{syst}$

When two versions of the R_0 determinations are available, we averaged these values. These results are given in Table 2.

Table 2: Mean values of R_0

Reference	R_0, kpc	
[20]	8.7 ± 0.7	8.9 ± 0.7
[21]	7.6 ± 0.4	8.3 ± 0.5
[22]	7.9 ± 0.85	8.2 ± 0.9
[23]	8.6 ± 0.7	8.8 ± 0.4
[24]	7.95 ± 0.62	8.25 ± 0.79
[25]	7.96 ± 0.63	8.36 ± 0.37
[26]	7.7 ± 0.7	7.8 ± 0.6

Asymmetric confidence intervals, rather than rms uncertainties, are provided as estimates of the accuracy in some studies [25,27,28]. In these cases, the uncertainties are taken to be the mean values of the lower and upper bounds of the intervals. Since these bounds are close to each other in all cases, this substitution does not appreciably affect our results.

The final list of all the R_0 values used is presented in Table 3.

3 Data analysis

The existence of a trend in the published R_0 values has been suggested in various earlier studies [2-4,6,62]. A systematic time-dependent decrease in published R_0 values during 1970-1990 was found in [2,3,6,62]. Although these data are mainly of historical interest now, this first suggestion of the presence of a bandwagon effect in R_0 determinations seems to have been based on a time-dependent drift in the data [62]. At the same time, the data for 1990–1998 do not show any significant trend [6], while the data of [3] show a slight positive trend, i.e., a small increase in R_0 values with time during 1990–2003. A large positive trend was found in [4] using results obtained in 1992–2010.

These results are somewhat contradictory, although we must bear in mind that they sometimes refer to different observing intervals. The conclusions of the papers cited above are based on various samples of published results, so that they could be distorted by selection effects in the data used.

To resolve this contradiction, we analyzed all available determinations of R_0 indicated in the previous Section (see Fig. 1). The epoch for a given R_0 value, taken to refer to the date of publication, is plotted along

Table 3: Results of R_0 determinations

R_0, kpc	STD	Reference	R_0, kpc	STD	Reference
7.9	0.8	[29]	8.05	0.6	[22]
8.1	1.1	[30]	8.3	0.3	[31]
7.6	0.6	[32]	7.7	0.15	[33]
7.6	0.4	[34]	8.01	0.44	[35]
8.09	0.3	[36]	8.7	0.6	[23]
7.5	1.0	[37]	7.2	0.3	[38]
7.0	0.5	[39]	7.52	0.36	[14]
8.8	0.5	[20]	8.1	0.7	[24]
7.1	0.5	[40]	7.4	0.3	[41]
8.3	1.0	[42]	7.94	0.45	[15]
8.21	0.98	[43]	8.07	0.35	[16]
7.95	0.4	[21]	8.16	0.5	[25]
7.55	0.7	[44]	8.33	0.35	[13]
8.1	0.4	[45]	8.7	0.5	[28]
8.5	0.5	[46]	7.58	0.40	[47]
7.66	0.54	[48]	7.2	0.3	[49]
8.1	0.15	[50]	8.4	0.6	[51]
7.1	0.4	[52]	7.75	0.5	[26]
8.51	0.29	[53]	7.9	0.75	[27]
8.2	0.21	[54]	8.24	0.43	[18]
8.6	1.0	[6]	8.28	0.33	[17]
7.4	0.3	[8]	7.7	0.4	[55]
7.9	0.3	[56]	8.1	0.6	[57]
8.67	0.4	[10]	8.3	1.1	[19]
8.2	0.7	[58]	7.80	0.26	[59]
8.24	0.42	[60]	8.3	0.23	[61]

the horizontal axis in Fig. 1. This epoch was determined by the month of publication in the corresponding journal issue number, or taken from the ADS bibliographic database (usually, for conference proceedings). If it was not possible to determine the month of publication, we adopted the middle of the year as the date of publication. When the epochs for two results coincided, we shifted them both by 0.02–0.03 yr in opposite directions to separate the corresponding points in the graph.

We calculated two versions of a linear trend using the given data. In the first version, the weights for the original data were taken to be equal to the inverse squares of their uncertainties. The resulting trend is -0.0045 ± 0.0103 kpc/yr. We did not take the weights into consideration in the second version, resulting in the trend $+0.0075 \pm 0.0100$ kpc/yr.

A simple, but effective criterion can be used to detect trends or other low-frequency variations in the data, namely Abbe's criterion. This criterion is aimed at testing the hypothesis that all the mathematical expectancies of the analyzed measurements xi are equal. To test this hypothesis, we calculated the Abbe statistic, which is essentially the ratio of the Allan variance AV (whose applications to astronomical studies are described in detail in [63,64]) to the dispersion of the data D:

$$\begin{aligned} q &= \frac{AV}{D}\,, \\ AV &= \frac{\sum_{i=1}^{n-1}(y_i - y_{i+1})^2}{2(n-1)}\,, \\ D &= \frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}\,, \end{aligned} \tag{1}$$

where $\bar{x}$ is the mean of all the measurements x_i.

If there are appreciable low-frequency variations in the data, including trends, D will be appreciably

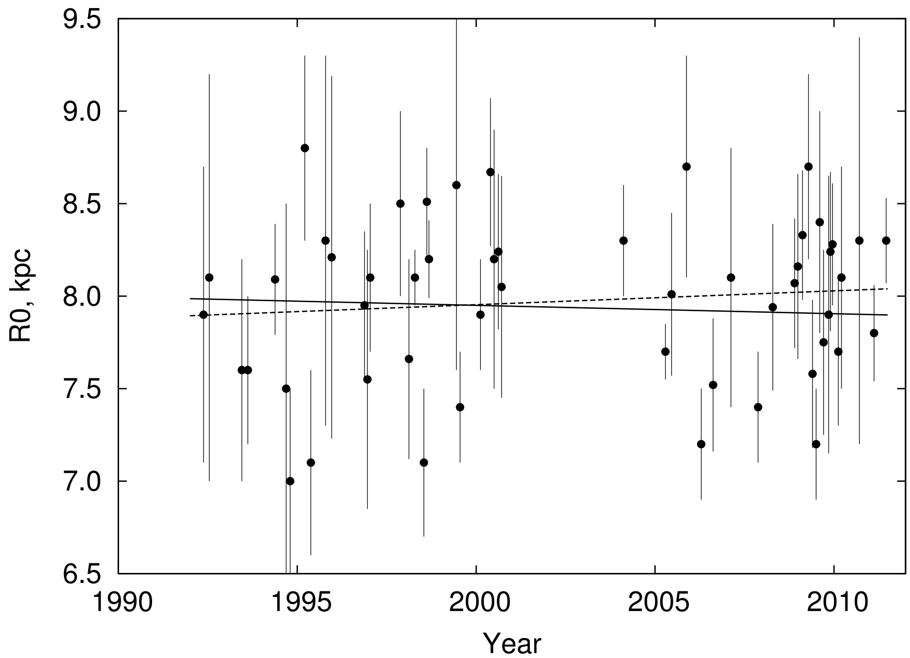

Figure 1: Values of R_0 used in this study. The solid and dashed lines correspond to the weighted and unweighted versions of the calculated trends, respectively.

greater than the Allan variance. Thus, if q is lower than the corresponding critical point of the Abbe distribution, the hypothesis that there is no trend must be rejected, and we conclude that there are statistically significant, systematic variations in the data. Our value is much greater than the 1% quantile for the Abbe distribution, which is equal to 0.69

Our conclusion based on all the calculations suggests that there are no statistically significant trends in the R_0 determinations for the last 20 years.

It is also interesting to consider how the accuracy of the R_0 determinations changes with time. This analysis was carried out using the data shown in Fig. 2, yielding the trend -0.0103 ± 0.0053 kpc/yr. Thus, there is a statistically significant decrease in the uncertainty of the R_0 determinations with time.

This conclusion seems all the more interesting because researchers have recently begun to pay more attention to estimate of the uncertainties of their results, including analysis of both statistical (formal) and systematic uncertainties. On the one hand, the uncertainties in R_0 should decrease with time as the observational data are accumulated and the observational and data-processing techniques are improved; on the other hand, these uncertainties could increase as new, more correct methods are used to estimate the accuracy. The former tendency has apparently been stronger in recent years.

4 Conclusions

Our analysis of 52 R_0 determinations published in 1992–2011 has shown that these data do not display a statistically significant trend, i.e., a systematic increase or decrease in the R_0 values with time. Therefore, we do not confirm the conclusions of Foster and Cooper [4], who found a large positive trend, i.e., a systematic increase in R_0 values, over the last 20 years. At the same time, we confirm the results of [3,6] indicating a slight trend, although on a shorter time interval.

The obvious origin of the discrepancy between our results and those of [4] is selection effects associated with the original data used in the analysis. This is clearly visible in Fig. 3, where our data and the data of [4] are shown. For some reason, the latter data did not include several R_0 values above the mean during the first half of the interval, as well as several values below the mean value during the second half of the interval, yielding an appreciable increase in the published R_0 values [4].

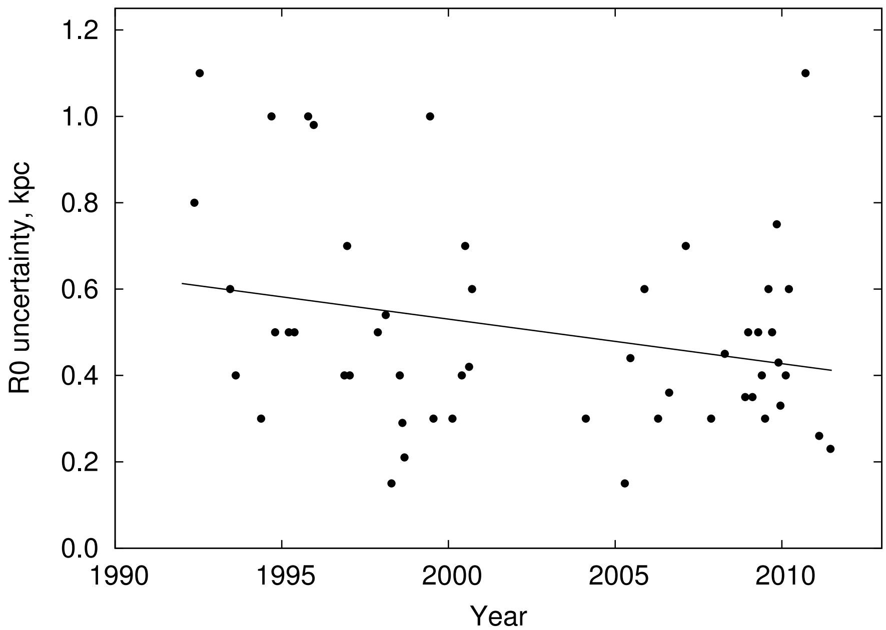

Figure 2: Uncertainties of the R_0 determinations, kpc.

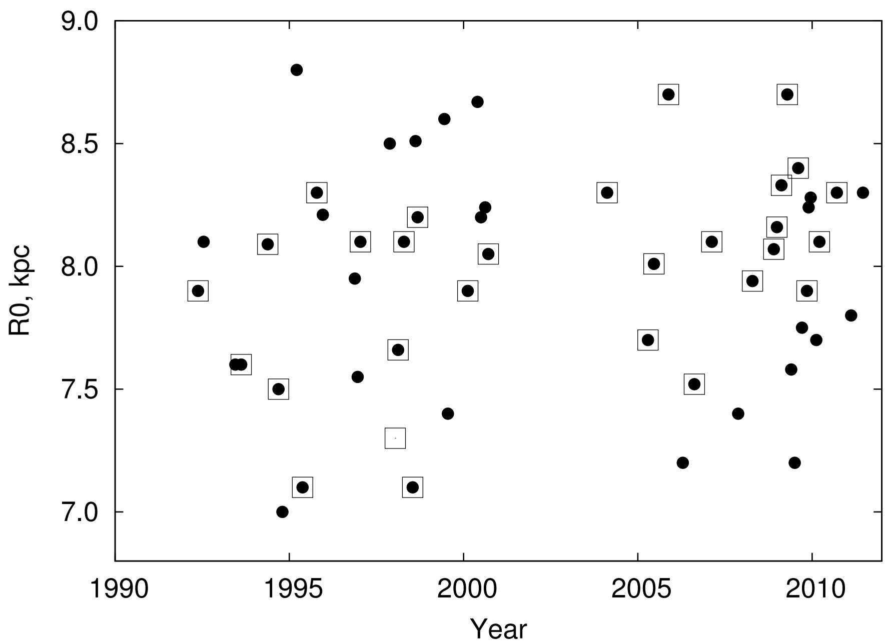

Figure 3: Sets of R_0 values used here and in [4] (the latter ones are denoted by squares), kpc.

In our opinion, our main conclusion that there is no statistically significant trend in the published R_0 values over the last 20 years suggests that these data do not contain a statistically significant bandwagon effect.

At the same time, we have discovered an appreciable decrease in the uncertainties of the R_0 determinations with time.

References

1. Z. M. Malkin, Astron. Rep. 55, 810 (2011).
2. M. J. Reid, Ann. Rev. Astron. Astrophys. 31, 345 (1993).
3. I. Nikiforov, in Order and Chaos in Stellar and Planetary Systems, Ed. by G. G. Byrd, K. V. Kholshevnikov, A. A. Myllari, et al., ASP Conf. Ser. 316, 199 (2004).
4. T. Foster and B.Cooper, in TheDynamic Interstellar Medium: A Celebration of the Canadian Galactic Plane Survey, Ed. by R. Kothes, T. L. Landecker, and A. G. Willis, ASP Conf. Ser. 438, 16 (2010); arXiv:1009.3220 [astro-ph] (2010).
5. F. J. Kerr and D. Lynden-Bell,Mon. Not. R. Astron. Soc. 221, 1023 (1986).
6. V. G. Surdin, Astron. Astrophys. Trans. 18, 367 (1999).
7. E. V. Glushkova, A. K. Dambis, A. M. Mel'nik, and A. S. Rastorguev, Astron. Astrophys. 329, 514 (1998).
8. E.V. Glushkova, A. K. Dambis, and A. S. Rastorguev, Astron. Astrophys. Trans. 18, 349 (1999).
9. B. Paczyński and K. Z. Stanek, Astrophys. J. Lett. 494, L219 (1998); e-Print arXiv:astro-ph/9708080 (1997).
10. K. Z. Stanek, J. Kaluzny, A. Wysocka, and I. Thompson, Acta Astron. 50, 191 (2000); arXiv:astro-ph/9908041 (1999).
11. F. Eisenhauer, R. Schödel, R. Genzel, et al., Astrophys. J. Lett. 597, L121 (2003); arXiv:astro-ph/0306220 (2003).
12. F. Eisenhauer, R. Genzel, T. Alexander, et al., Astrophys. J. 628, 246 (2005); arXiv:astro-ph/0502129 (2005).
13. S. Gillessen, F. Eisenhauer, S. Trippe, et al., Astrophys. J. Lett. 692, 1075 (2009); arXiv:0810.4674 [astro-ph] (2008).
14. S. Nishiyama, T. Nagata, S. Sato, et al., Astrophys. J. 647, 1093 (2006); e-Print arXiv:astro-ph/0607408 (2006).
15. M. A. T. Groenewegen, A. Udalski, and G. Bono, Astron. Astrophys. 481, 441 (2008), arXiv:0801.2652 [astro-ph] (2008).
16. S. Trippe, S. Gillessen, O. E. Gerhard, et al., Astron. Astrophys. 492, 419 (2008); e-Print arXiv:0810.1040 [astro-ph] (2008).
17. S. Gillessen, F. Eisenhauer, T. K. Fritz, et al., Astrophys. J. 707, L114 (2009); arXiv:0910.3069 [astro-ph] (2009).
18. N. Matsunaga, T. Kawadu, S. Nishiyama, et al., Mon. Not. R. Astron. Soc. 399, 1709 (2009); arXiv:0907.2761 [astro-ph] (2009).
19. M. Sato, M. J. Reid, A. Brunthaler, and K. M. Menten, Astrophys. J. 720, 1055 (2010), arXiv:1006.4218 [astro-ph] (2010).
20. I. S. Glass, P. A. Whitelock, R. M. Catchpole, and M. W. Feast, Mon. Not. R. Astron. Soc. 273, 383 (1995).
21. A. C. Layden, R. B. Hanson, S. L. Hawley, et al., Astron. J. 112, 2110 (1996); arXiv:astro-ph/9608108 (1996).
22. R. Genzel, C. Pichon, A. Eckart, et al., Mon. Not. R. Astron. Soc. 317, 348 (2000); arXiv:astro-ph/0001428 (2000).
23. M. A. T. Groenewegen and J. A. D. L. Blommaert, Astron. Astrophys. 443, 143 (2005); arXiv:astro-ph/0506338 (2005).
24. M. Shen and Z. Zhu, Chin. J. Astron. Astrophys. 7, 120 (2007).
25. A. M. Ghez, S. Salim, N. N. Weinberg, et al., Astrophys. J. 689, 1044 (2008); arXiv:0808.2870 [astro-ph] (2008).
26. D. J. Majaess, D. G. Turner, and D. J. Lane, Mon. Not. R. Astron. Soc. 398, 263 (2009), arXiv:0903.4206 [astro-ph] (2009).
27. M. J. Reid, K. M. Menten, X. W. Zheng, et al., Astrophys. J. 705, 1548 (2009); arXiv:0908.3637 [astro-ph] (2009).
28. E. Vanhollebeke, M. A. T. Groenewegen, and L. Girardi, Astron. Astrophys. 498, 95 (2009).
29. M. R. Merrifield, Astron. J. 103, 1552 (1992).
30. C. R.Gwinn, J.M.Moran, andM. J. Reid, Astrophys. J. 393, 149 (1992).

31. T. P. Gerasimenko, Astron. Rep. 48, 103 (2004).
32. J. M. Moran, M. J. Reid, and C. R. Gwinn, in Astrophysical Masers, Ed. by A. W. Clegg and G. E. Nedoluha, Lect. Notes Phys. 412, 244 (1993).
33. C. Babusiaux and G. Gilmore, Mon. Not. R. Astron. Soc. 358, 1309 (2005); arXiv:astro-ph/0501383 (2005).
34. W. J. Maciel, Astrophys. Space Sci. 206, 285 (1993).
35. V. S. Avedisova, Astron. Rep. 49, 435 (2005).
36. F. Pont, M. Mayor, and G. Burki, Astron. Astrophys. 285, 415 (1994).
37. I. I. Nikiforov and I. V. Petrovskaya, Astron. Rep. 38, 642 (1994).
38. E. Bica, C. Bonatto, B. Barbuy, and S. Ortolani, Astron. Astrophys. 450, 105 (2006); e-Print arXiv:astro-ph/0511788 (2005).
39. A.S.Rastorguev,O. V. Durlevich, E.D. Pavlovskaya, and A. A. Filippova, Astron. Lett. 20, 591 (1994).
40. A. K. Dambis, A. M. Mel'nik, and A. S. Rastorguev, Astron. Lett. 21, 291 (1995).
41. V. V. Bobylev, A. T. Baikova, and S. V. Lebedeva, Astron. Lett. 33, 571 (2007)]; arXiv:0709.4161 [astro- ph] (2007).
42. B.W. Carney, J. P. Fulbright, D. M. Terndrup, et al., Astron. J. 110, 1674 (1995).
43. D. Huterer, D. D. Sasselov, and P. L. Schechter, Astron. J. 110, 2705 (1995); arXiv:astro-ph/9508122 (1995).
44. M. Honma and Y. Sofue, Publ. Astron. Soc. Jpn. 48, L103 (1996); arXiv:astro-ph/9611156 (1996).
45. M. W. Feast, Mon. Not. R. Astron. Soc. 284, 761 (1997).
46. M. Feast and P.Whitelock, Mon. Not. R. Astron. Soc. 291, 683 (1997); arXiv:astro-ph/9706293 (1997).
47. A. K. Dambis, Mon. Not. R. Astron. Soc. 396, 553 (2009).
48. M. R. Metzger, J. A. R. Caldwell, and P. L. Schechter, Astron. J. 115, 635 (1998); arXiv:astro-ph/9710055 (1997).
49. C. Bonatto, E. Bica, B. Barbuy, and S. Ortolani, in Globular Clusters-Guides to Galaxies, Ed. by T. Richtler and S. Larsen (Springer, Berlin, Heidelberg, 2009), p. 209.
50. A. Udalski, Acta Astron. 48, 113 (1998); arXiv:astro-ph/9805221 (1998).
51. M. J. Reid, K.M.Menten, X.W. Zheng, et al., Astrophys. J. 700, 137 (2009); arXiv:0902.3913 [astro-ph] (2009).
52. R. P. Olling and M. R. Merrifield, Mon. Not. R. Astron. Soc. 297, 943 (1998); arXiv:astro-ph/9802034 (1998).
53. M. Feast, F. Pont, and P. Whitelock,Mon. Not. R. Astron. Soc. 298, L43 (1998).
54. K. Z. Stanek and P.M.Garnavich, Astrophys. J. Lett. 503, L131 (1998), arXiv:astro-ph/9802121 (1998).
55. A. K. Dambis, in Variable Stars, the Galactic Halo and Galaxy Formation, Ed. by C. Sterken, N. Samus, and L. Szabados (Sternberg Astron. Inst., Moscow Univ., Moscow, 2010), p. 177; arXiv:1001.1428 [astro-ph] (2010).
56. D. H. McNamara, J. B. Madsen, J. Barnes, and B. F. Ericksen, Publ. Astron. Soc. Pacif. 112, 202 (2000).
57. D. Majaess, Acta Astron. 60, 55 (2010); arXiv:1002.2743 [astro-ph] (2010).
58. I. I. Nikiforov, in Small Galaxy Groups, Ed. by M. J.Valtonen and C. Flynn, ASP Conf. Ser. 209, 403 (2000).
59. K. Ando, T. Nagayama, T. Omodaka, et al., Publ. Astron. Soc. Jpn. 63, 45 (2011); arXiv:1012.5715 [astro-ph] (2012).
60. D. R. Alves, Astrophys. J. 539, 732 (2000); arXiv:astro-ph/0003329 (2000).
61. A. Brunthaler, M. J. Reid, K. M. Menten, et al., Astron. Nachr. 332, 461 (2011); arXiv:1102.5350 [astro-ph] (2011).
62. M. J. Reid, in The Center of the Galaxy, Ed. by M.Morris, p. 37 (1989).
63. Z. Malkin, J. Geodyn. 82, 325 (2008); arXiv:physics/0703035 (2007).
64. Z. M. Malkin, Kinem. Phys. Celest. Bodies 27, 42 (2011); arXiv:1105.3837 [astro-ph] (2011).

Translated by N. Lipunova